NSF SBIR Phase 1 Proposal
Automated Transport Vehicle
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Overview

Key Words - Automation, robotics, disability assistance, infrared user tracking

People with disabilities need a device to more easily transport their possessions. The goal of this project is to create an ATV which can independently carry cargo, reducing bodily strain on the user. The ATV will be able to navigate through varied terrain and follow a user using an onboard Intel RealSense 3D camera, capable of providing RGB and depth imagery of the surroundings in front of the vehicle.

Intellectual Merit

This Small Business Innovation Research Phase I project implements qualities from various disciplines, including computer science, mechanical engineering, biomedical engineering, and systems engineering. The first technical challenge will be the construction of the ATV. In order to fulfill size, weight, portability and mobility requirements, the ATV will be stabilized by a Rocker-Bogie mechanism similar to that used by the Mars rovers. This will provide more freedom of movement, and let the ATV drive over curbs and small steps. The cargo compartment will remain relatively flat with the use of a differential gear system. This ATV leverages existing technologies, but combines them in a compact profile and with a simple-to-use interface that has not been seen before in other devices. User tracking will be accomplished with an Intel RealSense R200 3D camera. The produced video stream will be analyzed using the Intel RealSense SDK and new algorithmic components before providing navigational instructions to the ATV's motors. Consumer-grade computer vision systems and portable processing power have both reached an acceptable level of maturity, and our project will combine the two into a useful tool for disabled individuals. This RealSense SDK, in combination with other image processing and robotics tools available on the Windows operating system, will help to create and control the ATV.

Broader Impact

While the original intention of this project was to help disabled individuals carry heavy cargo without strain on the arms and legs, other use cases for this project exist. Elderly individuals and individuals with temporary handicaps will benefit greatly from this technology. Similar systems are in development to increase productivity at retail stores, malls, other marketplaces. An automated system that carries both heavy items and a large quantity of items around a store will benefit both customers and employees. This project expands upon extensive research done in the field of computer vision, user-tracking and robotics. However, there significantly less previous research in computer vision applications using complementary RGB and depth imagery, and this project hopes to build a foundation for this field of study.

Elevator Pitch

Times when one is required to carry large items, heavy items, or just too many items are frequent. A system that eliminates such a tedious chore would have many potential use cases. The elderly, handicapped, temporarily disabled, and customers and employees of large retail stores can reduce incredible amounts of bodily strain by letting an automated system transport heavy loads. The ATV will be able to achieve these goals of carrying heavy loads and autonomous operation using emerging technologies like the Intel RealSense Robotic Development Kit. The ATV will be able to follow a user through various terrain, over obstacles like curbs and stairs, and keep its cargo area safe and flat. An integrated computer will perform all image processing and navigation functions, allowing the ATV to follow its designated target.

The ATV is one of a few pioneers in autonomous personal transportation vehicles, yet none of these projects have provided reliable methodologies for user identification and tracking used in combination with robust object-avoidance capabilities. These competitors operate in previously mapped out environments using gathered location data, while the ATV constantly monitors its environment and target user.

This project presents numerous challenges, but incorporates techniques from computer science, mechanical engineering, systems engineering, and biomedical engineering disciplines. In order to fulfill size, weight, portability and mobility requirements, the ATV will be stabilized by a Rocker-Bogie mechanism similar to that used by the Mars rovers. A differential gear system will stabilize the cargo compartment, ensuring that the user's belongings remain unharmed during transportation.

The ATV has the potential to be an incredibly useful device, capable of providing support to individuals in the home, workplace, school and outdoor areas. It takes advantage of new image technology and mobile computing in order to preserve a lightweight construction and to promote energy-efficient operation. In addition to the direct benefits from using the ATV, the information learned from this research project can be used in future applications to create other devices that would benefit from autonomous, user-following capabilities.

The Commercial Opportunity

The target audience for this Automated Transport Vehicle is quite diverse and the potential avenues for monetization are numerous. This ATV is intended for individuals that are physically handicapped, temporarily handicapped, or non-disabled individuals trying to minimize the negative effects of daily lifting. This system will be suited for usage in various settings, and can become a valuable post-surgery recovery utility. With ample carrying capability condensed into a compact frame, this system can be stored in one's domicile and become an integral tool for reducing the intensity of a morning commute. This system can become as ubiquitous as crutches or slings in the road to surgical recovery, and will create profits once consumers and insurance companies realize the benefits of an ATV.

In recent years, the usage of robotics to assist with daily tasks has been increasing. The success of the Roomba has demonstrated that customers are willing to purchase high-end electronic systems to automate difficult tasks. The Roomba is still netting a profit for its parent company, iRobot, over a decade since its inception in 2002. Technology and robotics are becoming integrated into the daily lives of millions of people, and the ATV would easily take advantage of this trend and become a flagship utility. Twenty pounds may not sound like a large amount of weight, but daily lifting of twenty pound items can have devastating effects on one's back and body. Stress on the joints is often difficult to identify until it is too late for recovery. Many doctors recommend against the lifting of twenty pound objects while pregnant, as it can seriously increase the probability of a miscarriage.[1] Pregnant women, construction workers, mailmen, nurses, students, and many other individuals would benefit from having a mobile storage unit capable of following an individual.

Our ideal commercialization approach will begin with an aggressive marketing campaign conveying the diverse groups of people able to benefit from the purchase of an ATV. The marketing campaign would highlight the health and economic benefits associated with the ATV. By reducing the load an individual must carry, the ATV can both prevent injury and help expedite the recovery process for previous injuries. These health-related benefits can be translated into economic benefits, as time spent injured can negatively affect one's ability to earn income. For most of the workforce, time spent injured is time unable to earn a wage. However, with an ATV and the ability to easily transport one's required work materials, it becomes possible for a victim of health issues to recover and get back to work faster.

The ATV can also be used to increase the work efficiency of numerous occupations. A construction worker can load up a set of tools and machinery on an ATV, easily walk around the workplace, and put his effort towards actual construction tasks instead of lugging around materials. A nurse or doctor can fill an ATV with patient records and medical instruments, and spend more time assisting patients rather than trekking around the hospital while tracking down records. The technology and research obtained from pursuing this project can be put towards other related uses, such as automating the movement of shopping carts at a large retail or grocery store. A store that eliminates the task of pushing around a heavy cart would surely attract more customers. These customers would feel comfortable purchasing more items than when using a manual push cart, offsetting the store chain's initial investment in our technology and leading to significant rewards in the long run.

With a reasonable market-entry price of $300, this transport system would have many potential user bases. The ATV can become successful with accompanying advertisement campaigns and positive reviews travelling over the Internet or through word-of-mouth. At this price point, the cost of materials is offset, and a small amount of profit is earned to recuperate research and development costs. These profits can be then applied and used to fund a greater marketing campaign, injecting the ATV into more diverse markets. Extra funds may also be used to further support team research, leading to improved ATV functionality, design, and possibly newer versions of the system.

As excited as our team is to bring the ATV to the mass market, there are some possible risks to be encountered. Competition from other automated transport vehicles presents the

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[1] Occupational lifting of heavy loads and preterm birth: a study within the Danish National Birth Cohort, Nov 2013.

greatest risk to success in the market. There are similar products in various stages of development: some in early phases of development, few in prototyping and revision phases, and even fewer currently testing out the market. These are products that have autonomous cargo-carrying capabilities, but none so far combine that with individual user-tracking capabilities in dynamic environments. At some major international airports, robots are being implemented as mobile check-in locations, performing the printing of boarding passes and autonomously carrying luggage to proper luggage receptacles.[2] Other robotic systems are attempting the “last mile” of the delivery problem, which occurs when a shipment must reach a customer's doorstep. This requires visual and sensory analysis of dynamic locations to ensure the safe delivery of cargo.[3] There is little work being done to create a personal cargo carrier that focuses on the tracking of an individual, is not reliant upon previously-gathered map data, and can analyze and reroute itself based on encountered obstacles. This ATV will begin research into a new field of human-robot interactions and autonomous cargo carrying, and may encounter new regulations as a result.

In addition to risks from market entry, future legislation efforts also pose a minor threat. Technological capabilities have recently reached a point where autonomous robots are able to safely navigate urban environments. As a result, laws and regulations have been forced to keep up with such technological trends. The recent Personal Delivery Device Act of 2016 contains a small number of regulations for a new class of Personal Delivery Devices that our ATV falls under.[4] This act is brief, but outlines a few safety mandates making sure that this class of devices will not disrupt the flow of pedestrians, bicyclists, or car traffic. It also must have a manual override and alerting system in case of error. The ATV will conform to this Act with little modification to our current plans, but there lies the possibility of newer and more comprehensive legislation in the near future. The ATV, while technically autonomous, is always tracking a human “mentor”. This mentor not only serves as a target to follow, but also ensures that the robot is following proper traffic safety and in conformity with any future legislation.

There are many challenges that must be overcome in before a working version of the ATV is ready for production. However, with proper resources and planning, a market-ready ATV capable of helping the previously defined user groups ATV will be complete by the first quarter of 2017.

[2] https://www.sita.aero/innovation/sita-lab/leo-sitas-baggage-robot
[3] https://www.starship.xyz/
[4] https://trackbill.com/bill/dc-b673-personal-delivery-device-act-of-2016/1287806/

Societal Impact

The ATV has great potential in improving efficiency in the workplace and improving the health of customers by expanding the amount and weight of things an individual can easily carry. If used widely, the arduous task of lugging around a backpack or suitcase could become a remnant of the past. Of the nearly 80% of Americans who suffer from lower back pain, those who purchase an ATV would enjoy a reduction in pain after removing the transportation of heavy objects from their daily routines. Those recovering from injury would receive a huge productivity boost with a new method of transporting their work equipment, groceries, or other necessary cargo. However, with increased reliance on robotics to assist in daily tasks, some negative consequences arise.

The environmental impact of widespread use of the ATV and other similar Personal Delivery Devices is small, but still present. The ATV's construction promotes power efficiency in order to prolong battery life, but as with any motorized device, it consumes a considerable amount of power. Widespread usage of this ATV might also bring safety concerns to the forefront. A large part of this project is devoted to helping customers recover from injuries, and creating a product that possesses the ability to cause more injuries is counterintuitive. The ATV will weigh less than 30 pounds and travel less than five miles an hour. These physical restraints ensure that the ATV can only cause minimal disturbance to a pedestrian upon contact if object-avoidance capabilities fail. This element of safety is extended to the physical construction of the system as well.

The ATV will have a compartment that opens and closes slowly, minimizing the potential risk to children. The inner components, wires, and sensors will be contained within the skeleton of the device, ensuring children will not be harmed by this device and providing limited waterproofness. The final version of the ATV will be simple to operate, in order to accommodate our target audiences. A large portion of the user base will be disabled in some way, shape or form. As such, the ATV will be outfitted with simple user controls that require minimal human configuration and intervention. With numerous positive capabilities, we anticipate this device being put to good uses. Unfortunately, a few negative aspects have required planning in order to remediate.

As with any mobile storage area containing possibly expensive devices, theft poses a significant problem. In light of the potential for theft, the ATV will have an optional locking mechanism, ensuring that the cargo compartment can only be opened with consent of the owner. So far, the ATV does not have any protective measures to prevent theft of the whole system itself. We hope that the size and weight of the system combined with the fact that is always moving is enough of a deterrence factor. If this ends up being a prevalent, recurring issue, anti-theft countermeasures can be added to existing ATVs via a software update, and new models can have an extra anti-theft module built in. This anti-theft component is not included in the initial model, as we feel that this would be an inefficient usage of battery power and resources, as these resources would be better spent on robot navigation functions.

Once the ATV hits the market and becomes more commonly utilized, regulation may need to be implemented. As mentioned earlier, the Personal Delivery Device Act of 2016 is an early example of the type of legislation that can be expected. These expected regulation efforts will mostly be related to ensuring the safety of users and the public, and may be comparable to currently evolving drone regulations. Drones are not held accountable for causing injury or flying into restricted airspace. Instead, the pilots are held accountable, and the ATV will adhere to a similar policy. Therefore, an owner of an ATV will be held responsible for the proper usage of his system and any infractions that occur from user error or operation in an unlawful area. Legislation for the ATV is a welcome aspect of product creation, and we do not anticipate any potential requirements that would require complex modification in order to comply. We look forward to ensuring our product is lawful and helpful, and has far-reaching benefits.

Technical Discussion and R&D Plan

Technical challenges that may potentially hinder our innovation's entry to the market arise from the interlocking hardware and software components. Intel's product line of RealSense cameras only recently entered the market, and use cases for these cameras are actively being explored by early adopters. A small (3.5"x2.5"x1") single-board computer capable of powering our camera and performing motor operations will be housed inside the ATV's chassis. Like the RealSense, this single-board computer (known as the UP Board) is a newly developed product, having recently entered the market after its crowdfunded origins. The camera will be housed in the front, and will have a permanent, wired connection to the UP Board. Using the Intel RealSense SDK, this computer will process the RGB and Depth streams using various algorithms developed during our Phase 1 research. This SDK has basic user-detection capabilities already, which will be modified and incorporated into the multi-threaded application initiated by ATV.

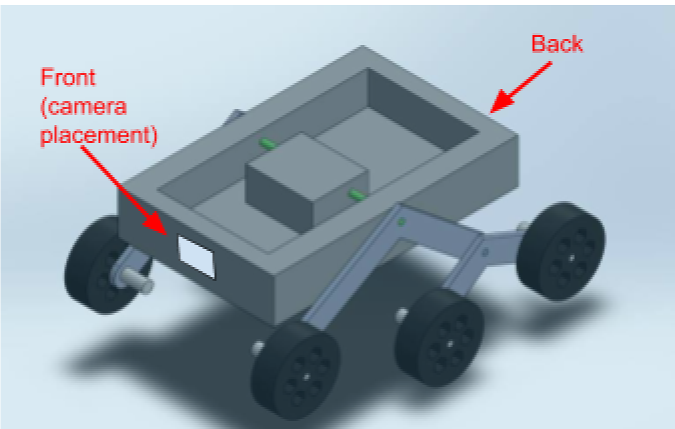

Figure 1: Rocker-Bogie Chassis

Multiple scenarios exist that make this user-following system a technical innovation and achievement. The most basic use-case exists when the target user walks alone and in a straight line: the ATV can constantly see the user, and maintain a specified distance away from the target using depth imagery. The user stays within the field-of-view of both the RGB and depth cameras, so no extra calculations must be performed in order to identify the location of a target user. Samples of these RGB and depth imagery streams can be seen below. This is the simplest use case, and will be the first one tested.

Unfortunately, this simplistic scenario is highly unlikely to occur during normal usage of the ATV and other use cases must be anticipated. While autonomous navigation is occurring, there may be some instances during which the ATV is unable to locate a target user. This failure may be due to environmental conditions like like lighting changes, encountered obstacles, or the target user making quick changes in direction. The user may be temporarily washed out by the sun, and the ATV will need to be able to maintain course and wait for conditions to stabilize. The target user may quickly turn a corner and disappear behind a wall. Another person may walk in between the ATV and its target user, and temporarily interrupt the constantly running user-tracking algorithms. In both cases, the ATV will have to


Figure 2: RGB and Depth Streams

rely on a stored cache of previous user positions. This cache provides the ATV with a basic understanding of object permanence, so it will recognize that the user still exists even when the user is not directly visible by either camera. This cache will be accessed when the user is not visible, guiding the ATV to the last known location of the user and reinitiating the user-tracking process. Once the ATV reaches this location, the user-tracking thread will resume control, identify the user, and instruct the motor processes to catch up to the target user. If the target user is still unable to be found, the robot must cease movement, alert the user, and then wait until it finds the target again.

Once user-tracking is successfully accomplished, Phase 1 research will move on to creating an object-recognition and avoidance system. This system consists of a new algorithm that complements the user-tracking capabilities of the ATV and will help take advantage of the multi-terrain capabilities of the Rocker-Bogie construction. This design choice offers the ability to climb objects like curbs and other small debris, but in doing so creates new challenges that must be overcome. When climbing over an object, the front wheels of the chassis become elevated, pointing the camera upwards, and again making a target disappear from the camera’s field of view. There will be six motors to control the six wheels defined in the ATV design and each one should be independently controlled. This independent control comes into to effect when the ATV initiates climbing over an obstacle, during which the motors may require separate levels of torque, separate voltages applied to each motor, and separate controls sent to each motor from the motor control system. The motor control system must be integrated with the other main control components, the significant components being the user-tracking and object-avoidance algorithms.

The software controlling the ATV will have multiple, concurrently-running processes that must communicate with one another and the accompanying hardware. At the highest level, this software and hardware interaction is illustrated in the following diagram. The primary method of obtaining input data is from the Intel RealSense R200. This camera will capture RGB data while simultaneously capturing images from two stereoscopic infrared cameras. It then uses these two images to produce the depth image, which can then be used to detect users and objects. Intel’s RealSense SDK uses C++ to capture, render, and analyze input data.

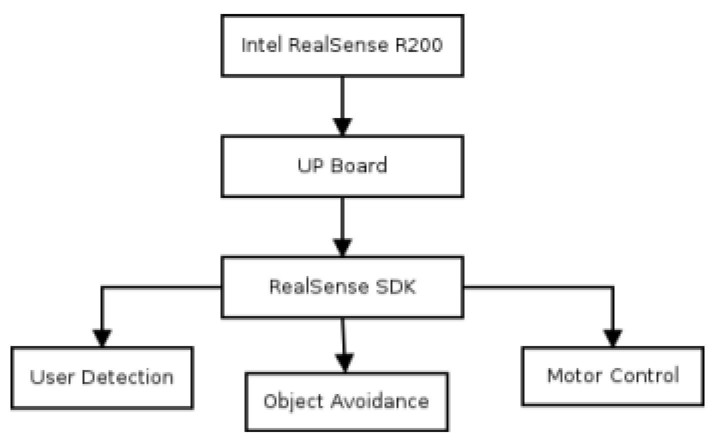

Figure 3: Hardware/Software Interaction

In order to promote efficiency and increase the ease with which later phases of development are accomplished, the interactions between various ATV components have been meticulously thought out and illustrated. The four main areas of focus for the ATV are: (1) robot construction, consisting of the suspension mechanism, (2) the cargo enclosure, (3) user identification, and (4) object avoidance. Each area of focus has accompanying risks, and methods have been identified to either eliminate or reduce the consequences of such risks. Overcoming these risks are important milestones in ATV development, and a significant amount of effort during phase 1 development will be spent implementing the solutions outlined in Appendix ii. Each one of these areas of focus will require testing to validate. The suspension mechanism can be determined successful if it supports all hardware components as well as the required maximum cargo load of 20 pounds as specified in Appendix I. The enclosure can be tested to see if it opens, closes, and keeps the cargo safe during transportation. The success of user identification and object avoidance is a little more difficult to evaluate, but a subjective means of doing so is still feasible. As mentioned before, situations that present an issue for the ATV will be outlined and appended to the existing list in Appendix ii. These error-causing scenarios will require an algorithmic solution, and the user identification and object avoidance systems will be refined using agile methodologies and extensive testing.

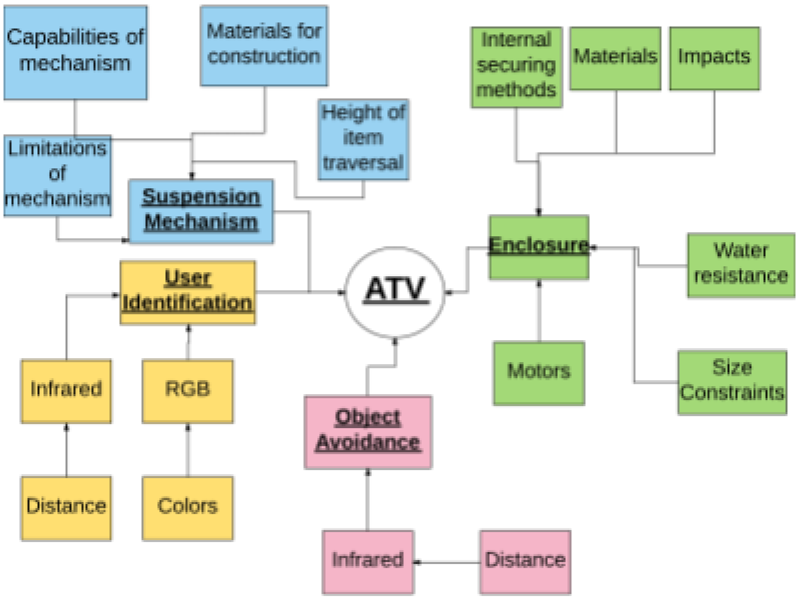

Figure 4: Four areas of focus

In order to meet required deadlines, the ATV team has created and will adhere to the following research and development timeline. The selected dates will enable the development team ample time to answer questions identified during preparatory phases as well as phase 1. Future work is pending a new investment, but keeping aligned with these proposed dates should not pose an issue.

	Task Name	Duration	Start Date	End Date	Predecessors	% Complete
1	Project Initiation	24d	09/09/16	10/12/16		100%
2	Camera Configuration	49d	10/04/16	12/09/16		80%
3	User Tracking	30d	11/14/16	12/23/16		40%
4	Object Avoidance Algorithm Implementation	26d	01/17/16	02/19/16		0%
5	Chassis/Compartment Construction	25d	01/17/17	02/20/17		0%
6	Component Integration	16d	02/19/17	03/10/17		0%
7	Testing and Troubleshooting	24d	03/13/17	04/13/17		0%

Figure 5: R&D Plan and Timeline

Constructing and designing the ATV will require a lot of experimentation in order to refine the underlying algorithms. In order to ensure that the the ATV fulfills all requirements, specifications, and use-cases, the ATV will be tested in the various locations and environment types. The ATV must be able to operate in urban, suburban and rural settings to maximize profitability, and copious amounts of test data will need to be gathered to ensure desired functionality in a diverse set of environments. Through a series of iterative testing practices and demonstrations, the progress of migrating the ATV from planning to production can be easily. By the first quarter of 2017, the ATV team hopes to have a fully-functional prototype which can then be utilized in the next phases to bring the system to the market.

Appendix i: Requirements and Specifications

Requirements	**Specifications**
Robot Construction	
Must support a carry-on suitcase	- Minimum size of cargo area: 22x14x9 inches based on TSA/airline carry-on bag size - Carry maximum load of 20 pounds, with a factor of safety of 1.5
Must be lightweight	- Weigh less than 30 lbs
Cargo must be secure	- Cargo area must be enclosed and openable - Cargo and robot body must be able to withstand impacts of and remain undamaged by 200 N (a kick)
Must have a mobile power source	- Power system components for a minimum of 1 hour
Water Resistance	- Must be able to qualify for an IP 21 rating
Must be safe to use	- Must close with no more force than 2 Nm to prevent injury to user
Cameras must be protected	- Cameras will be in watertight containment unit, protecting them from impacts and environmental threats
Environmental Constraints	
Must be able to navigate through GW campus environment	- Fit through standard 36” door frame - Climb standard 6” curb while carrying load - Climb maximum incline of 30° - Cargo must remain secure when max incline and/or max speed are reached
User must be able to navigate normally throughout environment	- Follow user moving at a speed up to 5 mph
Object Identification	
Must distinguish user	- Minimum FOV of the camera must be 90° in the vertical direction given working distance of 6 feet

	- Identify and track original user in all situations including: 1) Obstacles in between user and ATV 2) User exits camera's field of view
Must be able to categorize obstacles	- Distinguish between objects that are climbable versus ones that require a route modification
User Interface	
Must be easy to operate	- Loading cargo and running device should each be 1-command operations

Appendix ii: Risk Analysis

Risk	Cause	Mitigation
Losing User	User bending	After bending, user should pause to ensure robot follows
	Changes in lighting	User should walk slower and closer to the robot
	Crowded setting	
	User changes direction quickly	User should walk slower. Robot will go to last known location of user, then scan in previous direction of movement
	User goes into non-traversable area	Robot will scan for user. Alert via alarm if user is not found
	Robot get stuck trying to traverse over obstacle	Robot will scan for user. Alert via alarm if user is not found
	Person of similar stature and color walks in frame.	Robot will have continuously track and store user's last location, so it will be able to keep up by comparing new location relative to last location
ATV being physically impaired (whole system or certain parts)	ATV hits an obstacle	Use strong materials for ATV construction. Securely fasten all parts of ATV (camera, motors)
	ATV is hit by a passerby	Use strong materials for ATV construction. Securely fasten all parts of ATV (camera, motors)
Camera physically moves	Unsecure placement	Secure the camera onto the mount using at least two methods to hold it in place.
Motorized lid fails to open or close	Motor failure	User will be able to physically open and close lid without strain
Belongings are damaged	Flimsy construction materials for enclosure	Use strong, durable materials
Belongings are damaged	Robot falls over	Decrease height of whole system, increase base width, decrease speed, make wide turns